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A Toolset for Navigation in Virtual Environments

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ABSTRACT

Maintaining knowledge of current position and orientation is frequently a problem for people in virtual environments. In this paper we present a toolset of techniques based on principles of navigation derived from real world analogs. We include a discussion of human and avian navigation behaviors and show how knowledge about them were used to design our tools. We also summarize an informal study we performed to determine how our tools influenced the subjects' navigation behavior. We conclude that principles extracted from real world navigation aids such as maps can be seen to apply in virtual environments.

KEYWORDS: Navigation, Orientation, Virtual Worlds, Cognitive Maps

INTRODUCTION

A major problem for users of virtual environments is maintaining knowledge of their location and orientation while they move through the space. Navigation is the process by which people control their movement using environmental cues and artificial aids such as maps so that they can achieve their goals without getting lost. We are studying navigation as part of a larger effort aimed at understanding how people can best understand and interact with virtual environments.

Our basic approach to this research begins with a characterization of the problem domain in terms of its key characteristics. This means we must develop a classification of virtual environments, navigational tasks, and orientation. We also want to consider human abilities, both innate and artificially enhanced. Based on our best understanding, we build tools to aid users in the navigational tasks we have identified. Empirical studies of the tools are then used to evaluate their effectiveness. In many cases, we hope to begin to understand why certain tools are more effective than others and to feed this knowledge back into our theoretical framework.

Even in the physical world, the natural navigational abilities of humans and other animals are not completely understood. When the world is a virtual one, the problem is exacerbated by the degradation of sensory cues resulting from poor resolution, device latencies, and other shortcomings of current technologies. As virtual spaces become larger, more abstract, and more dynamic, the cues and stimuli associated with the physical world may be lacking altogether.

This paper focuses specifically on navigation and the effects differing tools and environmental cues have on the way in which people perform a simple set of generic exploration and searching tasks. We will begin with a brief summary of a classification of virtual worlds intended to set the context for the rest of the paper. We will then summarize some hypotheses concerning navigational capabilities of humans and birds. Finally, we will describe a toolset of possible techniques we built based on these hypotheses and summarize an informal empirical study designed to determine how the tools themselves affect their users' behavior.

A PRELIMINARY CLASSIFICATION OF VIRTUAL WORLDS

There are many ways to classify virtual worlds. For our purposes we have concentrated on three attributes: *size*, *density*, and *activity*. We do not claim that this classification is either complete or precise. Many of the distinctions, e.g. dense vs. sparse, are clearly subjective. It is in fact one of the eventual goals of our research program to fill in or correct the details of the following and to provide objective measures for classifying virtual worlds.

Size

A small world is a world in which all or most of the world can be seen from a single viewpoint such that important differences among objects in the world can be discerned. An example of such a small world is the virtual wind tunnel [4, 5] where the user is placed in a space containing only the space shuttle. An effect of small worlds is that they tend to focus attention on one object or a group of related objects.

A large world is defined by Kuipers and Levitt [10] as a "space whose structure is at a significantly larger scale than the observations available at an instant." We modify this, making it more geometric, by stating: there is no vantage point from which the entire world can be seen in detail. This keeps us consistent with our definition of a small world.

An infinite world is one in which we can travel along a dimension forever without encountering the "edge of the world." If a world is infinite in all its dimensions, it is a fully infinite world. If it is infinite in only *n* of its dimensions, it is semi-infinite in *n* dimensions.

Density

A sparse world has large open spaces in which there are few objects or cues to help in navigation. An example of this is a simulation of the surface of the ocean which is populated by only a few objects of interest; ships. Experience has shown that subjects in such a space easily become disoriented [6].

A dense world is characterized by a relatively large number of objects and cues in the space. An example of this would be the simulation of an urban area with many closely spaced buildings. The interiors of the buildings are also dense worlds.

A cluttered world is one in which the number of objects is so great that it obscures important landmarks or cues. A good example of this is the office of one of the authors; we leave the determination of which author as an exercise. Many information spaces are cluttered.

Another aspect of density is the way in which objects are distributed throughout a space. As the distribution approaches uniformity, the positions of objects become much more predictable. On the other hand, if objects are found clustered around a relatively small number of locations, a space with a relative number of objects sufficient to be dense can actually be sparse.

Activity

The level of activity of objects within a world is also an important consideration in designing navigational tools. A static world, in which the positions and values of the objects do not change over time, represents the simple end of the activity scale. A variation on static worlds, where the positions of objects are static but their values can vary, adds a bit of complexity to the navigation problem because the appearance of objects used as landmarks might change. In general, static worlds provide the most controlled environments and are the logical arena for preliminary study.

Dynamic worlds are worlds in which objects move about, thereby increasing the complexity of the navigational task. The movement of objects can be deterministic, that is they may follow predetermined paths, or nondeterministic, that is their paths are random in some sense. Worlds can be characterized along a continuum from fully determined, where all of the objects move deterministically, to fully nondetermined, where all objects move randomly.

NAVIGATION

The word "navigation" originally referred to the process of moving across a body of water in a ship. It has been extended to include the process of determining the path for a ship, an airplane, or even a spacecraft. We feel comfortable using the term in an even more general way — the process of determining a path to be traveled by any object through any environment.

Physiological & Psychological Perspective

In the animal kingdom, species often display great acts of navigation during migration or foraging. Avian physiology, in particular, has adapted to the need for navigation during annual migrations. Although research has not produced definitive answers to the riddle of avian migration, there exists evidence indicating the use of advanced perceptual abilities to detect and encode environmental cues [1]. It is believed that birds use a sophisticated landmarking technique in which a cognitive map is created. Landmarks on this map may be visual, acoustic, or olfactory. The availability of resources such as shelter and water is encoded along with information concerning the shortest and safest paths between points. The ability to fly greatly increases the bird's viewing range but also increases the size and complexity of the cognitive map. Increased altitude enables spatial relationships to be refined since more landmarks can be seen simultaneously, but increased altitude also decreases the strength of the stimuli. Visual details diminish along with acoustic and olfactory information whose source is on the ground.

Humans are also thought to form cognitive maps of their environments for use in navigation [7, 8, 16]. Lynch [11, 12, 13, 14] developed a set of generic components which he hypothesized are used to construct cognitive maps of urban environments. They include:

- *Paths*: linear separators, examples include walkways and passages.
- *Edges*: linear separators, such as walls or fences.
- *Landmarks*: objects which are in sharp contrast to their immediate surroundings, such as a church spire.

Technique	Real World Analog
flying	avian navigation
spatial audio	avian landmarking
breadcrumb markers	trailblazing
coordinate feedback	global position indicator
districting	urban environmental cues
landmarks	urban environmental cues
grid navigation	contour map orientation
mapview	map organization & presentation methodologies

Table 1: Navigation techniques in the toolset.

- *Nodes*: sections of the environment with similar characteristics. For example, a group of streets with the same type of light posts.
- *Districts*: logically and physically distinct sections. In Washington, D.C., they might be Foggy Bottom, Capitol Hill, etc.

Through the ages, humans have developed techniques for navigation and piloting to compensate for their perceptual system's limited ability to effectively utilize the physical cues available in nature. As humans began to range over vast distances in unfamiliar terrain, methods of maintaining orientation and position were developed. The primitive technique of dead reckoning is used today as a simple yet effective navigation method. The navigator marks the present position and orientation. This information is used, along with the distance traveled in a straight line, to determine a future position [3]. Trailblazing is performed in a similar fashion. Typically, physical markers are left behind to encode past positions or information concerning those positions for future retrieval. A more modern tool is the global position indicator which utilizes two satellite signals to accurately determine latitude and longitude. This information can be used with a local map for accurate navigation.

One of the most effective tools for navigation is, of course, the map. Physical map organization and display and the relationship between the physical map and its associated cognitive map are also at issue. Boff and Lincoln [2] present three fundamental design principles for maps:

- The two-point theorem states that a map reader must be able to relate two points on the map to the corresponding two points in the environment. This will orient the space properly to facilitate the map's use for navigation.
- The alignment principle states that the map should be aligned with the terrain. That is, a line between any two points in space should be parallel to the line between those two points on the map.
- The forward-up equivalence principle. The upward direction on a map always shows what is in front of the viewer.

In addition to traditional maps, Simutis and Barsam [15] describe the use of contour maps for navigation and orientation. The terrain contour itself is used as a cue to maintain direction.

The Navigation Toolset

We have implemented a toolset which consists of a subset of the navigation techniques used in the physical world. Table 1 lists the techniques and, for each of them, the real world analog which we used as our guide in developing each technique.

For virtual worlds which are similar in dimension to the physical world, the ability to fly offers the same advantages to humans that it does to birds in the physical world.

A spatial audio cue, a steady positional tone generated using the Audio Cube (by Visual Synthesis Inc.)* is used as an acoustic landmark. This is currently our only non-visual modality.

A system of marking the space with a visual marker (a simple unmarked cube which we call a breadcrumb) was implemented. This mechanism can be used manually, requiring the user to specify where markers should be dropped, or automatically, dropping markers at a constant frequency along the user's path.

A coordinate feedback system displays a textual readout of either Cartesian or polar coordinates of the subject's

*. The Audio Cube uses a cube of eight external speakers rather than headphones to position the sound sample.

current position. This is similar to the type of information available from the global position indicator.

Synthetic landmarks can be placed in the world. These landmarks are distinct from other objects in the space and are placed randomly when the environment is created. This is in contrast to breadcrumbs which may be generated throughout a scenario.

The world can be subdivided into districts (See Physiological & Psychological Perspective). Our districts do not coincide literally with Lynch's [11, 12, 13, 14]; rather, a set of visible lines are drawn in the world to divide it into smaller spaces. This is similar to showing political boundaries on a map, except that these are drawn in the world.

A map linked to the viewpoint is our final tool. This map can be either aligned with the world or aligned with the viewpoint. The distinction is related to the map organization and presentation methodologies previously described by Boff and Lincoln [2].

AN INFORMAL STUDY OF NAVIGATION TOOL EFFECTS

For our initial study, we chose a virtual environment that is both simple and relatively similar to a physical environment. The world consists of a large rectangular plane which can be randomly filled with a varying number of typical objects.† Since we are interested in observing the effects of a fairly large number of different tools on their user's behavior, we also focused on only three different forms of search: *exploration*, where the primary goal is gaining familiarity with the environment; *naive search*, where the subject is searching for an object when its appearance but not its location, is known; and *informed search*, when the subject has some knowledge about the location of the object.

The study included nine subjects, seven male and two female‡ all of whom have a technical background and are experienced computer users. Only three of the subjects had any experience using the apparatus and none had any previous knowledge of the subject matter of the study. A Fake Space Labs, Inc. BOOM2C display was used for high resolution, monochromatic display and mechanical tracking. The Audio Cube by Visual Synthesis Inc. was used for the spatial audio.

For each trial, a large world was randomly configured based on the number of objects required (sparse or dense world) and the tools to be made available. The relative size of the largest objects and landmarks to the world was approximately 1:100. The initial viewpoint location was marked with a flat square on the ground plane and the target was placed randomly at some minimal distance from the initial viewpoint location. The ground plane was represented as a square grid. The objects were identical ships. The target was a small pyramid. One button on the BOOM2C was used for forward movement in the view direction and the other for backward movement. Movement speed was not variable and movement through the ground plane was not allowed. Due to the use of primarily distant viewing, stereoscopy was not utilized.

Before their initial participation, subjects were informed as to the nature of the study and what they would be seeing in the worlds. Before each treatment, subjects were given information about the structure or representation of the tool(s) to be used but were never prompted with suggested strategies. For example, the components of the mapview and the orientation of the coordinate systems were described but subjects were not told how to use the tools. The task was described as having three primary parts:

1. Move through the space at will trying to view as much space as possible.
2. Search for the target object.
3. On cue, return to the start position.

Each subject was instructed to browse the space in an investigative fashion. Spatial knowledge gathered in this step is useful in the subsequent search tasks. At some random time before the target was visible to the subject, each was told to search for the target object. After moving sufficiently close to the target, an audible bell would sound signalling the subject to return to the initial position (marked by a square). During each trial, subjects were asked to freely describe choices being made, strategies, and general actions.

Subject behavior was recorded in written notes documenting observations made by the evaluator and comments made by the subjects during and after each trial. Of particular interest was data on positional or orientational information being gleaned from the environment or the tools and strategies used to accomplish any part of the task. Each scenario of tool(s) and world type was tried by different subjects until a generalization could be made on behavior in that scenario. Typically, five to six trials per scenario were used.

Observations

In Tables 2 through 5 we show the consensus behavior of the subjects for each treatment. The three generic elements (explore the space, find the target, return to the starting point) of the task are broken down into specific sub-elements reflecting the ways in which the subjects pursued their goals.

†. We used ships since the closest physical analog is a large tract of open sea.

‡. Although some studies have indicated gender variance in navigational behavior, we did not observe any gender based differences.

Landmark Scenario

The landmarks we used were simple rectangular columns, but they were considerably larger than the ships (figure 1). Subjects began by scanning the space from the starting location. They attempted to locate easily identifiable configurations of landmarks or clusters of ships. If they were able to locate a configuration of landmarks which also provided directional information, such as an "L" shape, their homing performance was improved.

1	Without moving, get orientation from objects in the space
1.1	Inspect landmarks for directional information
1.2	Inspect objects for directional information
2	Move through the space using landmarks as separators
2.1	Inspect each section partitioned by the landmarks
2.2	Maintain the direction of home
3	Locate the target object
4	Move in the direction of home until the space is familiar

Table 2. Landmark navigation behavior summary

When subjects began moving through the space they attempted to use landmarks to separate the space into segments. If the landmarks were configured in such a way as to make it difficult to use them as separators, subjects had a tendency to become disoriented and repeatedly search the same space. During this searching phase, subjects were also trying to maintain a direction for home.

During the homing phase, all subjects initially moved in an inaccurate direction indicating that their ability to maintain an accurate home direction was poor. Furthermore, those subjects who were unable to glean any directional information from landmark configuration were forced to perform the same kind of exhaustive search to find their way home that they had performed to find the target in the first place.

When a synthetic sun was added, all subjects' performance in both phases of the search improved. The landmarks were still used to separate the search space and make the search for the target more efficient but the sun provided much better directional information. This seems to result from two characteristics of the sun; its relative immobility and its visibility throughout the space make it an absolute directional marker. In contrast the most distinctive configurations of landmarks can only provide directional information relative to a local region.

Coordinate Tools Scenario

The coordinate tools give continuous numeric feedback of the subject's absolute position within the space. Subjects determined their orientation by making exploratory movements and observing how their coordinates changed. With Cartesian coordinates, the subjects tended to align their view direction with one of the axes of the world grid and move back and forth while observing changes in the coordinates. They would then turn ninety degrees and repeat the back and forth movement. With polar coordinates, subjects tended to combine small back and forth movements with sweeping from side to side.

1	Remember the home coordinates
2	Move experimentally to get orientation information
2.1	Spatial movements
2.2	Sweeping movements
3	Random movements to find the target
4	Use the tool for homing
4.1	Get orientation information (same as 2)
4.2	Move straight until close
4.3	Use textual information for accuracy

Table 3. Coordinate tool navigation behavior summary

Figure 1: Landmarks and ships.

The coordinate tools proved most useful for the homing task. Subjects were able to remember the coordinates of their starting place and quickly recognized the relationship between their current and starting positions. In both cases the subjects tended to treat homing as a separable task, where movement and searching were performed disjointedly [9]. We feel that this task separation is an artifact of the tools rather than something that is inherent in the task. With the polar tool, subjects would first adjust the bearing and then the range or vice versa. With the Cartesian tool subjects treated movement in x and y separately. The Cartesian coordinate tool was also somewhat useful in the target search since it could be used easily to partition the space into quadrants.

Breadcrumbs (or Hansel and Gretel Scenario)

The breadcrumb marker method was originally intended to be used as a trail making mechanism but was found to be used more as a manual landmarking technique where subjects would mark positions in space with semantic information. Subjects typically would mark the start position to simplify their return later in the trial. This was done in such a way as to be directional (See Landmark Scenario). The criteria for dropping a marker depended on the strategy being employed. If an exhaustive search was required, markers were dropped at a regular frequency in space to mark places as searched. If dead reckoning was being performed, markers were dropped along a straight line between two positions. Subjects also attempted to create a directional indicator with the markers showing a direction change if possible.

The markers were represented as cubes which hovered just above the ground plane. This hovering characteristic was used by subjects to see the markers at a distance and simplified the homing task somewhat, but it was noted that this also was a cause of some visual clutter.

Subjects exhibited behavior similar to that in the landmark treatment. Since the markers were nondirectional, maintaining orientation was a problem. Only relative information was available from the markers. Breadcrumbs were also used in an automatic mode in which markers were dropped at some set frequency in time. This technique was useful only for leaving a trail or as a method of marking searched spaces because it was not directly in the subject's control.

Flying Scenario

When we allow flying as a means of movement, we are effectively adding the third spatial dimension as a tool if we keep the navigation task two-dimensional. This is reflected in the initial action taken by subjects, flying up to get a bird's-eye view of their surroundings. They then maintained their altitude while searching for the target. The "fly where you look" style of movement made this difficult but a relatively steady altitude could be maintained with slight up and down fluctuations. This has the effect of changing the scale at which they view the world and is somewhat analogous to using a map. A map is, after all, a small scale representation of important characteristics of a space. The major difference is that, when flying in this way, a subject is combining map reading, navigation and movement into a unified task. A further indication that the subjects are integrating these tasks is the nature of their flight path. Subjects tended to simultaneously move the BOOM and depress a movement button yielding parabolic changes in direction. Simultaneous movement and change of direction was almost never observed in any of the other treatments.

1	Increase altitude until detail begins to be insufficient
2	Move around the space
2.1	Remain at set altitude while moving
2.2	Maintain the direction of home
3	When the target is located, lower altitude to get to it
4	Return to home
4.1	Increase altitude to the previous height
4.2	Move in the direction of the home marker
4.3	When located, lower altitude to the marker

Table 4. Flying navigation behavior summary

Mapview Scenario

The map in our mapview tool appears to float within the lower part of the field of view so that the subject can consult it at will by glancing down, yet it does not obscure the environment when the subject is looking around. The map shows the locations of; the starting point, ships, landmarks (if present), and the subject (figure 2). The

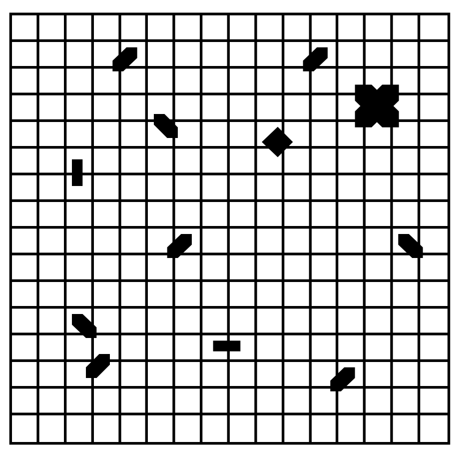

Figure 2: Schematic illustrating the map for mapview. X represents the start point and the diamond is the "you are here" marker. Other symbols represent ships; no landmarks are shown.

two treatments of mapview differ in their rules for orientation. In the view-aligned treatment, the map is always oriented with its top in the direction of the subject's view (figure 3a). This is analogous to navigating in a car with the map on your lap and its top oriented towards the dashboard regardless of the direction in which the car is moving. This behavior is characteristic of travel between cities. Our other treatment, world-aligned, keeps the map in constant alignment with the coordinate system of the world (figure 3b). This is somewhat analogous, in the car navigation example, to twisting the map so that the street you are driving along is aligned with its representation on the map. People tend to exhibit this behavior when they want to make sure they are turning in the correct direction at the next corner. Only this treatment satisfies the alignment and forward-up principles.

Because the map includes the starting point, it was unnecessary for the subjects to remember its location. Each version of mapview had both advantages and disadvantages. The view-aligned version was more useful for exhaustively searching the space. Subjects appear to have formed a more complete cognitive map of the environment since their view of the map did not vary as they moved. On the other hand, it was necessary for them to move and watch this motion reflected by the "you are here" indicator on the map in order to determine their orientation. With the world-aligned version, subjects had no difficulty determining their orientation from the map since it conforms to the alignment principle. However, maintaining world alignment causes the map to appear to rotate when the subject changes direction. This makes it harder to maintain a consistent cognitive map of the environment and hence decreases the usefulness of the map as an aid for exhaustive search.

1	Orient start position with the map
2	Move through the space
2.1	No need to maintain direction to home
2.2	Maintain previously viewed parts of the world
3	When the target is found, get direction to home from the map
4	Map used to get close
5	World view used for precision

Table 5. Mapview navigation behavior summary

Figure 3a: View aligned version of mapview.

Figure 3b: World aligned version of mapview.

Other Methods

Other treatments implemented and studied include districting, spatial audio, and grid navigation. Districting was implemented as a visual subdivision of the world into four quadrants. The districts allowed subjects to "chunk" spatial information necessary for learning and searching tasks into pieces. Searching was performed sequentially by district. Districts could be combined together to form an image of the world as a whole.

A spatial audio signal was added to the start location as a cue for the homing task. The cue was not audible throughout the world and thus offered no information when outside its range. When it became audible, it was used for rough direction finding. The spatial audio cue had the effect of enlarging the target object.

Lastly, when no other cues were available, subjects resorted to using the ground plane grid itself as a cue. The grid cannot offer assistance in position (unless an edge is used in a finite world). The orientation information available is cognitively demanding to maintain because it is purely relative information and requires attention to the grid at all times. If the grid included contour information [15], orientation would become easier and even positional information might be available.

CONCLUSIONS

Our purpose in this paper has been to investigate design principles for aids to navigation in virtual environments. We began by considering how humans and birds use environmental cues to aid navigation in the real world. We also looked at the principles of cognitive map formation and map design and understanding developed by cartographers and planners. Based on this background we chose and implemented a set of tools for navigation in a very simple virtual environment. An informal empirical study of the tools for a small set of searching tasks supports the following general conclusions:

- People tend to take advantage of environmental cues in predictable ways. They use them to partition spaces as an aid to exhaustive search. They use them to maintain direction relations performing best when the cue is statically positioned or highly predictable in its motion and when it is visible from the entire environment.
- Cues in different modalities, e.g. visual and audible can be combined to make targets easier to find.
- The tools they use have strong influences on people's behavior. Our subjects showed very different behavior when they used different tools. The variation among tool treatments was much larger than the variation among subjects.
- Because the navigation tasks were constrained to be two-dimensional and were performed on a two-dimensional surface, cartographic design principles could be extended from the real world to the virtual world. Had we included a three-dimensional task, such as a hunt for a spacecraft in an asteroid belt, we doubt that our mapview would have been of much use.

These conclusions, although far from definitive, are suggestive and encourage us to consider extending our research. We must form more specific hypotheses about how design principles relate to environmental characteristics and test them with more formal studies. We also intend to extend the research to virtual environments which have less in common with the real world. We hope that by doing this in a careful and gradual way, we will be able both to extend existing principles into new domains and to develop new principles for tool building in virtual environments.

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